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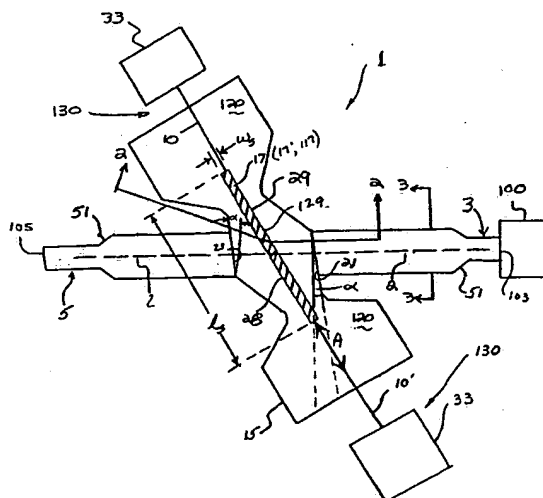
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(54) Title: OPTICAL WAVEGUIDE AND SHUTTER



(57) Abstract: An optical device having a shutter selectively moveable in and along a trench defined between an input waveguide and an output waveguide. Each waveguide has a core defined therethrough that defines an optical path through the device and which traverses the trench. The trench intersects the optical path and the shutter may be moved into and out of the optical path or within the optical path. By selectively moving the shutter into and out of the trench, and into and out of the optical path, an optical signal propagating in and through the waveguide may be conditioned. The shutter may be sized and shaped to attenuate an optical signal passing through the trench when the shutter intersects the optical path. Alternatively, the shutter may have at least one aperture defined therethrough to provide chopping of an optical signal passing through the trench by selectively moving the shutter in the trench so as to alternatively block the optical signal and allow the optical signal to pass from one waveguide to the other.

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## **OPTICAL WAVEGUIDE AND SHUTTER**

### **CROSS-REFERENCE TO RELATED APPLICATIONS**

This application is a Continuation-In-Part of U.S. Patent Application Serial Number 09/718,671, filed on November 22, 2000. This application also claims priority to Provisional Patent Application Serial Number 60/180,566, filed on February 4, 2000, and Provisional Application Serial Number 60/180,564, filed on February 4, 2000.

### **FIELD OF THE INVENTION**

The present invention is directed to an optical device for attenuating or chopping an optical signal as it propagates in and through a waveguide.

### **BACKGROUND OF THE INVENTION**

Typically, an optical signal (the terms "light signal" and "optical signal" are used interchangeably herein and are intended to be broadly construed and to refer to visible, infrared, ultraviolet light, and the like), is guided by a waveguide along an optical path; the optical path typically being defined by the waveguide core. It may become necessary or desirable to condition the optical signal; the term condition being used herein to refer to attenuating or chopping (generally defined as periodic interruption of a beam of light so as to produce regular pulses of light) an optical signal.

Attenuation may be desirable if the optical power of an optical signal exceeds a desired level. For example, an optical signal carries digital data from a source to a destination, and may be amplified as the optical signal travels between the source and destination. However, the destination device, component, system, etc., may have limitations

on the magnitude of optical signal it can receive or detect. It may thus be desirable or necessary to reduce the power level of the optical signal to ensure that it is within acceptable limits of the receiving device, etc. An attenuator, such as an attenuating shutter, for example, selectively placeable in the optical path may serve that purpose.

It may also be desirable to chop an optical signal to generate a reference signal having a predetermined frequency, for example. An optical chopper, such as a shutter having an opening defined therethrough, for example, selectively movable into and out of the optical path may serve that purpose.

When conditioning an optical signal, it is important to do so without adversely affecting the data characteristics of the signal. For example, if attenuation is desired, it should be accomplished without changing the phase of the optical signal and without introducing error into the data carried by or represented by the optical signal. When chopping is the desired result, it is necessary to ensure that the "chopped" optical signal has sufficient integrity so as to serve as a reference optical signal.

Size is also an ever-present concern in the design, fabrication, and construction of optical components (i.e., devices, circuits, and systems). It is clearly desirable to provide smaller optical components so that optical devices, circuits, and systems may be fabricated more densely, consume less power, and operate more efficiently.

### **SUMMARY OF THE INVENTION**

The present invention is directed to an optical device having a shutter selectively moveable in and along a trench defined between an input waveguide and an output waveguide. Each waveguide has a core defined therethrough that defines an optical path through the device and which traverses the trench. The trench intersects the optical path and

the shutter may be moved into and out of the optical path or within the optical path. By selectively moving the shutter into and out of the trench, and into and out of the optical path, an optical signal propagating in and through the waveguide may be conditioned.

The input waveguide and the output waveguide have respective cores that define an optical path through the optical device; those cores being aligned or coaxial with each other. Those waveguides are also separated by the trench, the trench having a medium provided therein that has a refractive index that may be different from that of the waveguides. The input and output waveguides are separated by a distance, i.e., the trench width (generally defined as the distance between the waveguide facets 21, 23 (see, e.g., FIG. 1)) insufficient to affect the transmission characteristics of an optical signal propagating from the input waveguide to the output waveguide, even though the optical signal may experience different refractive indices as it propagates from the input waveguide to the output waveguide. Thus, even though an optical signal passing from the input waveguide to the output waveguide must completely traverse the trench, the distance over which the optical signal must travel between the waveguides is small enough so as to not affect the optical transmission characteristics of that signal. That is, while the trench is large enough to allow for the finite thickness of the shutter to be selectively moved within the trench or into and out of the trench, the trench is also as small as possible to minimize light diffraction that typically occurs when an optical signal propagates unconfined (as occurs in the trench).

In a first embodiment, the shutter is sized and shaped to attenuate an optical signal passing through the trench when the shutter is located in the optical path. An optical device constructed in accordance with the first embodiment of the present invention has an input for receiving an optical signal from an optical source and an output. The inventive optical device comprises an input waveguide having an output facet and a waveguide core, and an output

waveguide having an input facet and a waveguide core aligned generally coaxially with the input waveguide core. The input waveguide core and output waveguide core define an optical path through the optical device along which the optical signal may propagate. The optical device further comprises a trench defined between the first and second waveguides. The trench has a width defined by a distance between the respective facets of the input and output waveguides. An attenuator shutter is disposed in the trench and caused to move between a first position and a second position by an actuator. When the shutter is in the first position, it is not disposed in the optical path and the optical signal does not pass through the attenuator shutter. When the shutter is in the second position, the optical signal passes through and is attenuated by the attenuator shutter.

In a second embodiment, the shutter has an aperture defined therethrough and provides chopping of an optical signal passing through the trench by selectively moving the shutter in the trench so as to alternatively block the optical signal and allow the optical signal to pass through the aperture from one waveguide to the other. An optical device constructed in accordance with the second embodiment has an input for receiving an optical signal from an optical source and an output. The optical device comprises an input waveguide having an output facet and a waveguide core, and an output waveguide having an input facet and a waveguide core aligned generally coaxially with the input waveguide core. The input waveguide core and output waveguide core define an optical path through the optical device along which the optical signal may propagate. The first and second waveguides are separated by a trench having a width defined by a distance between facets on the input and output waveguides. The inventive optical device further comprises a chopper shutter having an aperture defined therethrough and being disposed in the trench. A first actuator is connected to a first end of the shutter, and a second actuator is connected to a second end of the shutter.

The first and second actuators cause the shutter to move between a first position in which the optical signal is blocked by the shutter from traversing the trench, and a second position in which the optical signal passes through the aperture and traverses the trench.

The invention accordingly comprises the features of construction, combination of elements, and arrangement of parts which will be exemplified in the disclosure herein. The scope of the invention will be indicated in the claims.

### **BRIEF DESCRIPTION OF THE DRAWINGS**

In the drawing figures, which are not to scale, and which are merely illustrative, and wherein like reference characters denote similar elements throughout the several views:

FIG. 1 is a top plan view of an optical device constructed in accordance with the present invention;

FIGS. 2A and 2B are cross-sectional views of two embodiments of the optical device of the present invention taken along line 2-2 of FIG. 1;

FIG. 3 is a cross-sectional view of a waveguide of the optical device taken along line 3-3 of FIG. 1;

FIG. 4 is a cross-sectional top view of an embodiment of an electrothermal actuator provided as part of an optical device in accordance with the present invention;

FIG. 5 is a top plan view of another embodiment of an electrostatic actuator provided as part of an optical device in accordance with the present invention;

FIG. 6 is a top plan view of a further embodiment of an electrostatic actuator provided as part of an optical device in accordance with the present invention;

FIG. 7 is a top plan view showing a close-up of a portion of a tapered portion of the input waveguide of FIG. 1;

FIG. 8 depicts a flip-chip assembly of an optical device in accordance with an embodiment of the present invention;

FIGS. 9A and 9B are perspective views, respectively, of fixed-width and a tapered attenuator shutter constructed in accordance with embodiments of the present invention; and

FIG. 10 is a perspective view of a chopper shutter constructed in accordance with an embodiment of the present invention.

#### **DETAILED DESCRIPTION OF THE PRESENTLY PREFERRED EMBODIMENTS**

The present invention is directed to an optical device having a shutter selectively moveable in and along a trench defined between an input waveguide and an output waveguide. Each waveguide has a core defined therethrough that defines an optical path through the device and which traverses the trench. The trench intersects the optical path and the shutter may be moved into and out of the optical path. By selectively moving the shutter into and out of the trench, and into and out of the optical path, an optical signal propagating in and through the waveguide may be conditioned.

The input waveguide and the output waveguide have respective cores that define an optical path through the optical device; those cores being aligned or coaxial with each other. Those waveguides are also separated by the trench, the trench having a medium provided therein that has a refractive index that may be different from that of the waveguides. The input and output waveguides are separated by a distance, i.e., the trench width (generally defined as the distance between the waveguide facets 21, 23 (see, e.g., FIG. 1)) insufficient to

affect the transmission characteristics of an optical signal propagating from the input waveguide to the output waveguide, even though the optical signal may experience different refractive indices as it propagates from the input waveguide to the output waveguide. Thus, even though an optical signal passing from the input waveguide to the output waveguide must completely traverse the trench, the distance over which the optical signal must travel between the waveguides is small enough so as to not affect the optical transmission characteristics of that signal. That is, while the trench is large enough to allow for the finite thickness of the shutter to be selectively moved within the trench or into and out of the trench, the trench is also as small as possible to minimize light diffraction that typically occurs when an optical signal propagates unconfined (as occurs in the trench).

In a first embodiment, the shutter is sized and shaped to attenuate an optical signal passing through the trench when the shutter is located in the optical path. In a second embodiment, the shutter has a plurality of apertures defined therethrough and provides chopping of an optical signal passing through the trench by selectively moving the shutter in the trench so as to alternatively block the optical signal and allow the optical signal to pass from one waveguide to the other.

Referring now to the drawings in detail, and with initial reference to FIG. 1, an optical device 1 constructed in accordance with an embodiment of the present invention is there depicted. The optical device 1 of the present invention is preferably constructed of silica-based semiconductors (e.g.,  $\text{SiO}_2$ ). Other semiconductors such as, for example, GaAs and InP, also might be used. In addition, the waveguide construction described below is provided as an illustrative, non-limiting example of an embodiment of the present invention; other waveguide geometries and configurations are contemplated by and fall within the scope and spirit of the present invention.



The optical device 1 includes an input waveguide 3 and an output waveguide 5 arranged around and separated by a trench 15. An optical signal, provided by an optical source 100 (e.g., a laser, diode, or other light emitting or generating device), enters the device 1 via an input 103 of the input waveguide 3. That optical signal propagates in and along the input waveguide 3, traverses the trench 15, propagates in and along the output waveguide 5, and exits the device via an output 105 of the output waveguide 5. The optical signal may be conditioned as it traverses the trench 15, depending upon the type and position of a shutter 17 provided as part of the inventive optical device 1.

A cross-section of the input waveguide 3, which is also exemplary of the output waveguide 5, is depicted in FIG. 3. The following description of and reference to the input waveguide 3 shall also apply to the output waveguide 5. The waveguide 3 includes a substrate 13, preferably  $\text{SiO}_2$ , a lower cladding layer 9b disposed on the substrate 13, and an upper cladding layer 9a. A core 27 is provided on the lower cladding layer 9b and surrounded by the upper cladding layer 9a. The waveguide 3 is constructed using semiconductor fabrication techniques and methods known to those skilled in the art. For example, the substrate 13 may be first formed using known semiconductor deposition techniques. The lower cladding layer 9b and core 27 are deposited, in blanket position, with the core 27 being initially formed to the width of the substrate 13 and lower cladding layer 9b. The core 27 may then be etched to a desired core width,  $w_c$ , and the upper cladding layer 9a deposited on the lower cladding layer 9b and about the core 27 to form a buried waveguide configuration.

The waveguides 3, 5 may be formed from a wide variety of materials chosen to provide the desired optical properties. While it is preferable to construct the optical device 1 of the present invention on a silica-based ( $\text{SiO}_2$ ) platform, other semiconductors that provide the desired optical properties may also be used. For example, the core 27 might include

germanium-doped silica, while the upper and lower cladding 9a, 9b may include thermal  $\text{SiO}_2$  or boron phosphide-doped silica glass. That platform offers good coupling between the optical device 1 and an external optical component such as, for example, a fiber-optical cable and a wide variety of available index contrasts (0.35% to 1.10 %). Other platforms which could be used include, by way of non-limiting example,  $\text{SiO}_x\text{N}_y$ , polymers, or combinations thereof. Other systems such as indium phosphide or gallium arsenide also might be used.

With continued reference to FIG. 3, the core 27 can have an index of refraction contrast ranging from approximately 0.35 to 0.70%, and more preferably, the index of refraction can range from approximately 0.35 to 0.55% to allow for a high coupling to an output fiber-optic cable. The core 27 may be generally rectangular, with a core thickness,  $t_c$ , ranging from approximately 3 to approximately 10  $\mu\text{m}$ , and a width,  $w_c$ , ranging from approximately 3 to approximately 15  $\mu\text{m}$  wide. More preferably, the core 27 is generally square, with a thickness ranging from approximately 6 to approximately 8  $\mu\text{m}$ , and a width ranging from approximately 6 to approximately 14  $\mu\text{m}$ . The upper and lower cladding layers 9a, 9b may have a combined thickness,  $t_{cl}$ , ranging from approximately 3 to approximately 18  $\mu\text{m}$ , and preferably approximately 15  $\mu\text{m}$ . Those dimensions are provided by way of example and not limitation.

Referring again to FIG. 1, the core 27 of input waveguide 3 is generally coaxial with the core 7 of the output waveguide 5. That coaxiality defines an optical path 2 along the waveguides' respective longitudinal length and the optical device's longitudinal length. Thus, the input waveguide 3 and output waveguide 5 may be considered to be arranged in registry with each other, with aligned or coaxial cores 27, 7, which maximizes the amount of light transferred from input waveguide 3 to output waveguide 5.

The trench 15 is defined in the substrate 13 (see, e.g., FIGS. 2A and 2B) and separates the input waveguide 3 and output waveguide 5, intersecting the optical path 2. The trench 15 is filled, partly or completely, with an optically transparent medium 120 such as, for example, air, having an associated index of refraction  $n$ . For air, the index of refraction is approximately equal to 1.00. The trench width (generally defined as the distance between the input waveguide facet 21 and the output waveguide facet 23) can range from approximately 8 to approximately 40  $\mu\text{m}$ , and preferably ranges from approximately 12 to approximately 20  $\mu\text{m}$ .

Referring again to FIG. 1, each of the waveguide cores 27, 7 have an associated index of refraction determined, at least in part, by the material from which the waveguide core 27, 7 is constructed. The associated index of refraction for the waveguide cores 27, 7 are approximately equal to each other, and is a value of approximately 1.45 for the silica platform. The medium 120 provided in the trench 15 also has an associated index of refraction that may be different than the waveguide refractive indices. If the medium is air, for example, its refractive index is approximately equal to 1.00. When an optical signal experiences different refractive indices as it propagates, certain characteristics of that signal may be caused to change as a result of the different indices. For example, part of the optical signal (in terms of optical power) may be reflected back into the input waveguide and along optical path 2. That reflected signal can propagate back to the optical source 100 and cause it to destabilize. Also, the optical signal may experience a phase shift when it passes from a material having a first refractive index to a material having a second and different refractive index. In some cases, that is a desired result. For the optical device 1 of the present invention, it is preferable that the optical signal not experience any significant change in its

optical characteristics as it is guided along and conditioned by the various components that make up the optical device 1.

To overcome the undesirable effects of the differing refractive indices, the present invention controls the distance between the output facet 21 of the input waveguide 3 and the input facet 23 of the output waveguide 5 so that the optical signal propagates too short a distance between the waveguides 3, 5 for the difference in refractive indices of the waveguides 3, 5 and medium 120 to introduce any significant change in the optical signal characteristics. Thus, even though the optical signal completely traverses the trench 15 (from input waveguide 3 to output waveguide 5), the optical signal does not experience any significant adverse affect due to the difference in the medium and waveguide respective refractive indices.

The difference in refractive indices may cause part of the optical signal (in terms of optical power) to be reflected and propagate backward along the optical path 2 into the input waveguide 3, for example; that phenomenon being generally referred to as optical return loss (ORL). Another aspect of the present invention compensates for ORL caused when an optical signal passes between materials having different refractive indices. The reflected signal can disadvantageously reflect back to and possible destabilize the optical source 100. By angling one or both of the output facet 21 of the input waveguide 3 and/or the input facet 23 of the output waveguide 5 with respect to the optical path 2, (see, e.g., FIG. 1), any reflected signal is directed away from the waveguide core 27 and toward the cladding 9a or 9b, thereby preventing the reflected light from interfering with the optical source 100 or with the optical signal being guided by and propagating in the input waveguide 3. In an embodiment of the present invention, one or both of the output facet 21 and/or input facet 23 may be disposed at an angle  $\alpha$  formed between the perpendicular to the optical path 2 and the surface at the

waveguide/trench interface. That angle may range from about  $5^{\circ}$  to  $10^{\circ}$ , and more preferably, from about  $6^{\circ}$  to  $8^{\circ}$ , to minimize the loss of light reflecting back into the input waveguide 3 due to ORL.

In another aspect of the present invention, ORL may be further minimized by applying an antireflective coating (not shown) on the waveguide facets 21, 23. The antireflective coating can be single layer or a multilayer structure. Such a coating can reduce reflection at the waveguide/trench interface from approximately 3.5% to below approximately 1% over a large range of wavelengths. The materials and thickness forming the antireflective coating layers are substantially the same as those used in thin film technology. For example, the best single layer antireflective coating between a silica waveguide and a trench at the wavelength of  $1.55\text{ }\mu\text{m}$  has a refraction index of 1.204 and a thickness of approximately 322 nm.

In yet another embodiment, ORL may be minimized by using a combination of the previously described angled interface and antireflective coating.

With continued reference to FIG. 1, a shutter element 130 includes a shutter 17 (either an attenuation shutter 17' or a chopper shutter 117) provided in the trench 15 and an actuator 33 coupled to the shutter 17 by link 10 for providing selective movement of the shutter 17 within the trench 15 and into and out of the optical path 2, as described in more detail below. For a chopper shutter 117, described in more detail below, the shutter element 130 includes first and second actuators 33, 33', each connected to an end of the shutter 17 by a link 10, 10'. Various embodiments of the actuator 33 are contemplated by the present invention including, by way of non-limiting example, electrothermal, electrostatic, and piezoelectric, each of which is described in more detail below.

The embodiment depicted in FIG. 1 is preferred for a chopper shutter 117 and includes a first actuator 33 and a second actuator 33' disposed at and connected to opposite

ends of the shutter 117. The dual actuator configuration of the chopper shutter 117 embodiment provides dual coaxial forces on opposite ends of the shutter 117 to ensure a generally uniform movement of the shutter 117 in the trench 15 and as described in more detail below.

The shutter 17 may comprise an attenuator shutter 17', as depicted in FIGS. 9A and 9B, or a chopper shutter 117, as depicted in FIG. 10; both of those embodiments being discussed in more detail below. For both of the just-mentioned embodiments, the shutter 17 is preferably made from a light yet stiff material such as silicon, polymers, metallic or dielectric materials. The shutter 17 can be a low-mass, thin film shutter that may be caused to move quickly in response to an electrical signal within the trench 15 or into and out of the optical path 2, as the case may be. For example, when the shutter 17 is configured as an attenuator shutter 17' (see, e.g., FIGS. 9A and 9B), the shutter 17' may be caused to move between a first position, in which the shutter is not in the optical path 2 and an optical signal does not pass through the shutter, and at least a second position in which the shutter 17 is in the optical path 2 and the optical signal passes through and is attenuated by the shutter 17'. (see, e.g., FIG. 1). When the shutter 17 is configured as a chopper shutter 117 (see, e.g., FIG. 10), the shutter 117 may be caused to move within the trench 15.

A first surface 29 of the attenuator shutter 17' may be coated with a film 129 that permits an optical signal to pass through the shutter 17' but that provides attenuation of that optical signal. The attenuator shutter 17' need not move very smoothly or be oriented with respect to the optical path 2 in a precise manner. The only requirement is that the shutter 17' be selectively movable into and out of the optical path 2 so as to either intercept and attenuate an optical signal propagating in and through the optical device 1, or permit the optical signal to traverse the trench 15 without interception or attenuation.

With continued reference to FIG. 1, and additional reference to FIG. 2A, the shutter 17 has a height  $h_s$  sufficient to intercept an optical signal; in the case of an attenuator shutter 17', the height  $h_s$  is sufficient to intercept and attenuate the optical signal, and in the case of a chopper shutter 117, the height  $h_s$  is sufficient to alternately block the optical signal and permit the optical signal to pass through the shutter 117. Preferably, the height of the shutter 17 is approximately equal to or greater than the core thickness  $t_c$  (see, e.g., FIG. 3), and ranges from approximately 10 to 100  $\mu\text{m}$  high, and more preferably, from approximately 30 to 40  $\mu\text{m}$ . The shutter length  $l_s$  (see, e.g., FIG. 1) is preferably minimized to reduce the distance required for the shutter 17 to be moved within the trench 15, as described in more detail below, while at the same time being long enough to intercept the optical signal. Minimizing the length of the shutter 17 also reduces the electrical power required to move the shutter 17 in and out of the optical path and improves the speed of the optical device 1. Again, to intercept the optical signal the shutter 17 has a length  $l_s$  that is preferably at least approximately equal to or greater than the core width  $w_c$  and ranges from approximately 10 to approximately 100  $\mu\text{m}$ , more preferably from approximately 20 to 70  $\mu\text{m}$  long, and most preferably from approximately 30 to 40  $\mu\text{m}$  long.

With continued reference to FIG. 1, and additional reference to FIGS. 9A and 9B, an attenuator shutter 17' will now be discussed in detail. The width  $w_s$  of the attenuator shutter 17' may be fixed, as depicted in FIG. 9A, or it may be tapered, as depicted in FIG. 9B. A fixed-width shutter 17' will provide a predetermined and constant attenuation, while a tapered shutter 17' can provide a range of attenuation, depending, at least in part, on the thickness of the shutter 17' encountered by the optical signal. The width of the fixed-width shutter 17' ranges from approximately 1  $\mu\text{m}$  to approximately 8  $\mu\text{m}$ , and for the tapered shutter 17, can range from approximately \_\_\_  $\mu\text{m}$  ( $w_{s1}$ ) to approximately \_\_\_  $\mu\text{m}$  ( $w_{s2}$ ).

Attenuation of the optical signal may also be controlled by application of a film 129 on a surface of the attenuation shutter 17'. While a film 129 is depicted on surface 29 in FIG. 1, the film 129 may alternatively be provided on surface 28, or on both surface 29 and surface 28.

The attenuator shutter 17' may be caused to move into and out of the optical path 2 when attenuation of an optical signal is desired. For example, if an optical signal enters the input waveguide 3 having an optical power level that may cause damage to a downstream optical component (e.g., an optical component connected to, but not comprising a part of, the optical device 1), that condition may be detected using a suitable optical power detector. In addition, the optical device 1 of the present invention can attenuate the optical signal by causing the attenuator shutter 17' to move into the optical path 2 and intercept and attenuate the optical signal. For a fixed-width attenuator shutter 17', movement of the shutter 17' into the optical path 2 so as to intercept the optical signal is sufficient. For a tapered attenuator shutter 17', different degrees of movement into trench 15 will present different thicknesses of attenuator shutter 17' into the optical path 2, providing a variety of degrees of attenuation. The shutter 17' must be more precisely positioned in the trench 15 so that the optical signal passes through a part of the shutter 17' having a thickness necessary to impart the desired attenuation.

Referring next to FIG. 10, a chopper shutter 117 will now be discussed in detail. The chopper shutter 117 may be used when it is desirable to alternately intercept and block the optical signal, and allow the optical signal to pass (i.e., traverse the trench 15) at predetermined intervals. Such a configuration may be used to provide a pulsed optical signal having a predetermined duty cycle. The shutter width,  $w_s$ , is preferably fixed and can range from approximately 1 to approximately 8  $\mu\text{m}$  (those dimensions also apply to a fixed-width



attenuator shutter), and more preferably is approximately 2  $\mu\text{m}$  thick. At least one aperture 170 is defined through the shutter 117 and is sized and shaped to permit an optical signal to pass therethrough without interference and without altering the optical signal. If more than one aperture 170 is provided in the shutter 117, the distance between apertures 170 need only be wide enough to block the optical signal. If a chopper shutter 117 is provided in an optical device 1 in accordance with an embodiment of the present invention, the shutter 117 may be caused to move in the trench 15 (as described in more detail below) in a generally oscillatory manner; moving back and forth so as to alternately intercept and block the optical signal, and permit the optical signal to traverse the trench 15 and pass from input waveguide 3 to output waveguide 5. The periodicity of the oscillation is a routine matter of design choice, and depends, at least in part, on the characteristics desired of the optical signal output from the optical device 1.

Generally uniform movement of the chopper shutter 117 is provided by oppositely located actuators 33, 33' (see, e.g., FIG. 1), that separately provide the force required to move the shutter between the first and second positions; alternately blocking the optical signal and permitting it to traverse the trench 15.

The shutter can be made from any sufficiently rigid and light material such as, for example, silicon.

With continued reference to FIG. 1, the input waveguide 3 may receive an optical signal (e.g., a WDM, DWDM, UDWDM, etc.) from an optical source 100 (e.g., a laser, laser diode, other optical component or light generating or propagating device, component or system). The optical signal is guided by the core 27 and propagates through and within the waveguide 3 along the optical path 2. The optical signal exits the input waveguide 3 via the output facet 21 and enters the trench 15. Depending upon the position of the shutter 17, the

optical signal will either propagate across the trench 15 and enter the output waveguide 5 via an input facet 23, or encounter a first surface 29 of the shutter 17.

If the shutter 17 is an attenuator shutter 17', the optical signal will pass through the shutter 17' and exit via a second surface 28 having an optical power level less than the optical power level of the optical signal that encountered the first surface 29. The amount of attenuation depends, at least in part, on the material from which the shutter 17' is constructed, the shutter width,  $w_s$ , and whether any film 129 is provided on either or both surface 29, 28. For a tapered attenuator shutter 17', the amount of attenuation may be controlled by selective positioning of the shutter 17' in the trench 15 and in the optical path 2. More attenuation may be achieved by positioning a thicker part of the shutter 17' in the optical path 2.

If the shutter 17 is a chopper shutter 117, the optical signal will either be blocked or pass through an aperture 170 in the shutter 117, depending upon the position of the shutter 117 in the trench 15 with respect to the optical signal and optical path 2.

With continued reference to FIG. 1, and with additional reference to FIGS. 2A and 2B, the actuator 33 of the shutter element 130 controls the movement of the attenuation shutter 17' or chopper shutter 117 in the trench 15. Movement of the shutter 17' or 117 may be in virtually any direction (e.g., along a plane parallel with or perpendicular to a bottom surface 150 of the trench 15), so long as that movement provides the ability to move the shutter 17' or 117 into and out of the optical path 2 (for an attenuator) or to move the shutter 17' or 117 within the optical path 2 (for a chopper). For example, FIGS. 1 and 2A depict a first embodiment of the shutter element 130 having a shutter 17' or 117 that is movable along a plane generally parallel with the plane of the bottom surface 150 of the trench 15 and in a direction generally indicated by arrow A (FIG. 1). It should be noted that the embodiment depicted in FIG. 1 is for a chopper shutter 117, and includes two actuators 33, 33'. An

attenuator shutter 17' embodiment will have a single actuator 33. For an attenuator shutter 17', the actuator 33 may cause the shutter 17' to move between a first position, in which the shutter 17' is not disposed in the optical path 2 and does not intercept and attenuate the optical signal, and at least a second position, in which the shutter 17' is disposed in the optical path 2 so as to intercept and attenuate the optical signal (and as depicted in FIG. 1). Precise positioning of the attenuator shutter 17' is not required, as the shutter 17' need only be selectively moved into and out of the optical path 2.

For a chopper shutter 117, the actuator 33 may cause the shutter 117 to move between a first position, in which the optical signal is blocked by the shutter 117 from traversing the trench 15, and a second position, in which the optical signal passes through an aperture 170 defined through the shutter 117. Somewhat more precise positioning is required for this embodiment (as compared to the attenuator shutter embodiment) because the shutter 117 must be aligned to block the optical signal or to permit it to pass through the aperture 170. Mispositioning of the chopper shutter 117 may cause the optical signal to be partially blocked.

Another embodiment of the configuration of the shutter element 130 is depicted in FIG. 2B in which the actuator 133 causes the shutter 17 (17' or 117) to move along a plane generally perpendicular with the bottom surface 150 of the trench 15 and in a direction generally indicated by arrow B.

While any suitable actuator could be used to implement the present invention, either an electrothermal or electromechanical type actuator is preferred.

For the purposes of this invention, it will be appreciated that any electrothermal actuator could be used which sufficiently changes its physical size in response to the application of thermal energy (which, it will be appreciated, could be generated by applied

electrical energy). One benefit to using electrothermal actuators is that such actuators may be latching-type devices, i.e., one that maintains its position without the continuous application of energy. This means that if suitably constructed, the actuator, once switched to one of two positions, will remain in that position until it is switched to its other position.

An exemplary electrothermal latching-type actuator 233 suitable for use with the present invention is depicted in FIG. 4. That actuator 233 includes a flexible member 34 which is securely fixed at endpoints 35, 35' to the walls of a cavity 37. Cavity 37 is sized and shaped to permit the movement of flexible member 34 as described in more detail below. Also provided is a heater or heating element 39, which is located in relatively close proximity with the member 34. The heater 39, when driven (e.g., by the application of current through contacts (not shown)), causes the member 34 to warm and expand. Since the member's ends are secured at endpoints 35, 35', the member 34 cannot simply expand so that the endpoints shift outward. Instead, compressive stresses will be generated along the member's length. These stresses increase until they reach a level sufficient to cause the member 34 to change its position. Thus, when the heater 39 is driven, the flexible member 34 also will be warmed and caused to move between an ambient position, indicated by reference character C, and a flexed position, indicated by reference character D. Alternatively, the member 34 could itself be the heater.

In accordance with another embodiment of the present invention, an electrostatic actuator may also be used to selectively move the shutter 17. Benefits of electrostatic actuators include high operating speed, low energy consumption, and minimal system heating. One type of electrostatic actuator 333 usable in connection with the present invention is depicted in FIG. 5. That actuator 333 includes electrodes 41, 41' located on opposite sides of a piezoelectric element 43 made from a material which expands in at least

one dimension (i.e., width or length) when an electric field is applied thereto (via the electrodes 41, 41'). Consequently, by applying an electric signal to electrodes 41, 41', an electric field is generated and piezoelectric element 43 will expand in the direction indicated by arrow E thus imparting movement to the shutter 17.

It is possible that one actuator alone may not be sufficient to provide the required amount of movement for the shutter 17. This can be rectified by providing a piezoelectric actuator 433 such as that depicted in FIG. 6, which includes a number of interlaced fingers 45. These fingers are attached to a support 20 within actuator 433, which serves to prevent unwanted motion of one side of the fingers 45. When an electrical signal is applied to electrodes (not shown) of the actuator 433 depicted in FIG. 6, the total displacement in the direction of arrow F of endpoint 47 will reflect the displacements of each of the fingers 45. Since the displacement of endpoint 47 is the sum of the fingers' individual displacements, a significant movement of the shutter 17 can be achieved. This type of electrostatic actuator 433 may require the application of substantial voltage, possibly on the order of 100 V, to obtain the desired movement of the shutter 17. Despite the magnitude of this potential, very little power is required, since the current flow through the electrostatic actuator 433 is negligible.

Another aspect of this invention relates to the shape of the waveguides 3 and 5 used to direct light to and from the switch 1. As recited by this aspect of the invention, and as shown in FIGS. 1 and 7, a tapered neck region 51 is provided on at least one of the waveguides 3 and 5 so that the waveguide width tapers to a smaller cross-section at a location 49 remote from the trench 15. Tapered neck 51 helps to reduce the diffraction of light in the trench 15. By way of non-limiting example only, in the region of the trench 15, the waveguide width,  $w_w$ , may be in the range of approximately 5 to 15  $\mu\text{m}$ . That width may taper to a range of

approximately 4 to 10  $\mu\text{m}$  at the remote location 49. These dimensions, it will be appreciated, are provided as illustrative, non-limiting examples of an embodiment of the present invention.

Tapered neck region 51 provides a smooth transition for the optical signal as it propagates through and is guided by the waveguides 3 and 5 (i.e., by the waveguide cores 27, 7). Tapered neck 51 confines the light traveling through the waveguide 3, 5, in accordance with known principals of waveguide optics, and greatly reduces the transition loss which would otherwise occur where light passes between waveguides having different dimensions. This is in contrast to the attenuation which would occur at a sudden transition from one width waveguide to a different width waveguide. Various taper rates for the tapered neck 51 may be used, depending upon the particular considerations of a given application of the optical device 1 of the present invention.

An optical device 1 constructed in accordance with the present invention may be assembled using a flip-chip manufacturing technique, such as that generally depicted in FIGS. 8A and 8B. In flip-chip manufacturing, the waveguides 3 and 5 and trench 15 are formed on a first chip 200, and the shutter 17 and actuator 33 are formed on a second chip 210. The various parts of the optical device 1 (e.g., waveguides 3, 5, trench 15, shutter 17, actuator 33, etc.) may be formed as previously described, as well as with other generally known semiconductor formation and fabrication techniques and methods. Prior to assembly of the two chips 200, 210, the two chips are oriented to face each other, aligned so that corresponding portions of the chips oppose one another (e.g., so that the shutter 17 is aligned with the trench 15), and then joined. Spacers 71 may be provided on one of the chips 200 or 210 to ensure proper distance between the various parts of the optical device 1.

In an alternative embodiment of the present invention, the optical device 1 may be constructed by monolithically forming the various parts of the device 1. In such an embodiment, the various parts of the optical device 1 are formed on a single substrate 13 through the selective deposition and removal of different layers of material using now known or hereafter developed semiconductor etching techniques and processes. One of the benefits of monolithic fabrication is that it avoids the need to register the different components before the two substrates are joined.

It should be understood that this invention is not intended to be limited to the angles, materials, shapes or sizes portrayed herein, save to the extent that such angles, materials, shapes or sizes are so limited by the express language of the claims.

Thus, while there have been shown and described and pointed out novel features of the present invention as applied to preferred embodiments thereof, it will be understood that various omissions and substitutions and changes in the form and details of the disclosed invention may be made by those skilled in the art without departing from the spirit of the invention. It is the intention, therefore, to be limited only as indicated by the scope of the claims appended hereto.

It is also to be understood that the following claims are intended to cover all of the generic and specific features of the invention herein described and all statements of the scope of the invention which, as a matter of language, might be said to fall there between. In particular, this invention should not be construed as being limited to the dimensions, proportions or arrangements disclosed herein.

**CLAIMS**

What is claimed is:

1. An optical device having an input for receiving an optical signal from an optical source and an output, said optical device comprising:

- 5           an input waveguide having an output facet and a waveguide core;
- an output waveguide having an input facet and a waveguide core aligned generally coaxially with said input waveguide core, said input waveguide core and said output waveguide core defining an optical path through said optical device along which the optical signal may propagate;
- 10           said first and said second waveguides being separated by a trench having a width defined by a distance between said input waveguide output facet and said output waveguide input facet, said optical path traversing said trench;
- an attenuator shutter disposed in said trench; and
- an actuator connected to said shutter for causing said shutter to move between
- 15   a first position in which said shutter is not disposed in said optical path and the optical signal does not pass through said attenuator shutter, and at least a second position which is out of said first position and the optical signal passes through said attenuator shutter, the optical signal being attenuated by said attenuator shutter when said shutter is in said at least second position.

20

2. An optical device as recited by claim 1, wherein said trench width ranges from approximately 8  $\mu\text{m}$  to approximately 40  $\mu\text{m}$ .



3. An optical device as recited by claim 2, wherein said trench width ranges from approximately 12  $\mu\text{m}$  to approximately 20  $\mu\text{m}$ .

4. An optical device as recited by claim 1, wherein said actuator is a latching  
5 actuator.

5. An optical device as recited by claim 1, wherein said attenuator shutter has a surface, said optical device further comprising a film on said surface for attenuating the optical signal when said shutter is in said at least second position.

10

6. An optical device as recited by claim 1, wherein at least one of said output and said input facets is angled with respect to said optical path.

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7. An optical device as recited by claim 6, wherein said facet angle ranges from approximately 5° to approximately and 10°.

8. An optical device as recited by claim 6, wherein each of said output and said input facets is angled with respect to said optical path.

20

9. An optical device as recited by claim 8, wherein said facet angle of each of said output and said input facets ranges from approximately 5° to approximately and 10°.

10. An optical device as recited by claim 1, wherein said attenuator shutter has a substantially constant width.

11. An optical device as recited by claim 1, wherein said attenuator shutter has a  
5 variable width.

12. An optical device as recited by claim 1, wherein said trench has a bottom surface and wherein said shutter is caused to move between said first and said second positions along a line generally parallel to said bottom surface.  
10

13. An optical device as recited by claim 1, wherein said trench has a bottom surface and wherein said shutter is caused to move between said first and said second positions along a line generally perpendicular to said bottom surface.

14. An optical device having an input for receiving an optical signal from an  
15 optical source and an output, said optical device comprising:  
  
an input waveguide having an output facet and a waveguide core;  
  
an output waveguide having an input facet and a waveguide core aligned  
generally coaxially with said input waveguide core, said input waveguide core and said output  
20 waveguide core defining an optical path through said optical device along which the optical  
signal may propagate;

said first and said second waveguides being separated by a trench having a width defined by a distance between said input waveguide output facet and said output waveguide input facet, said optical path traversing said trench;

5 a chopper shutter having an aperture defined therethrough and being disposed in said trench;

a first actuator connected to a first end of said shutter; and

a second actuator connected to a second end of said shutter, said first and said second actuators causing said shutter to move between a first position in which the optical signal is blocked by said shutter from traversing said trench, and a second position in which  
10 the optical signal passes through said aperture and traverses said trench.

15 15. An optical device as recited by claim 14, wherein said trench width ranges from approximately 8  $\mu\text{m}$  to approximately 40  $\mu\text{m}$ .

16. An optical device as recited by claim 15, wherein said trench width ranges from approximately 12  $\mu\text{m}$  to approximately 20  $\mu\text{m}$ .

17. An optical device as recited by claim 14, wherein each said actuator is a latching actuator.

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18. An optical device as recited by claim 14, wherein at least one of said output and said input facets is angled with respect to said optical path.

19. An optical device as recited by claim 18, wherein said facet angle ranges from approximately  $5^\circ$  to approximately and  $10^\circ$ .

20. An optical device as recited by claim 18, wherein each of said output and said  
5 input facets is angled with respect to said optical path.

21. An optical device as recited by claim 20, wherein said facet angle of each of said output and said input facets ranges from approximately  $5^\circ$  to approximately and  $10^\circ$ .

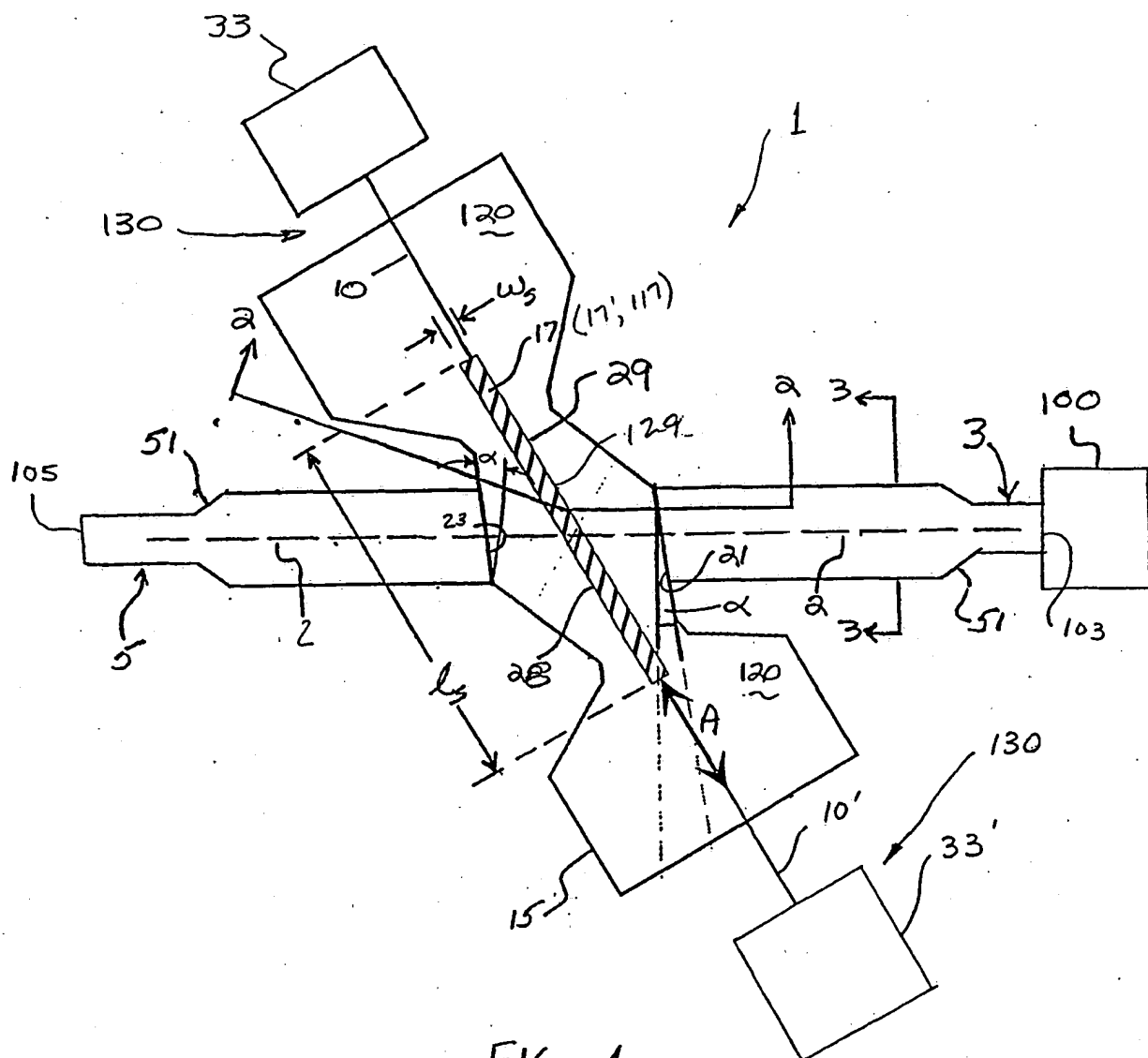


FIG. 1

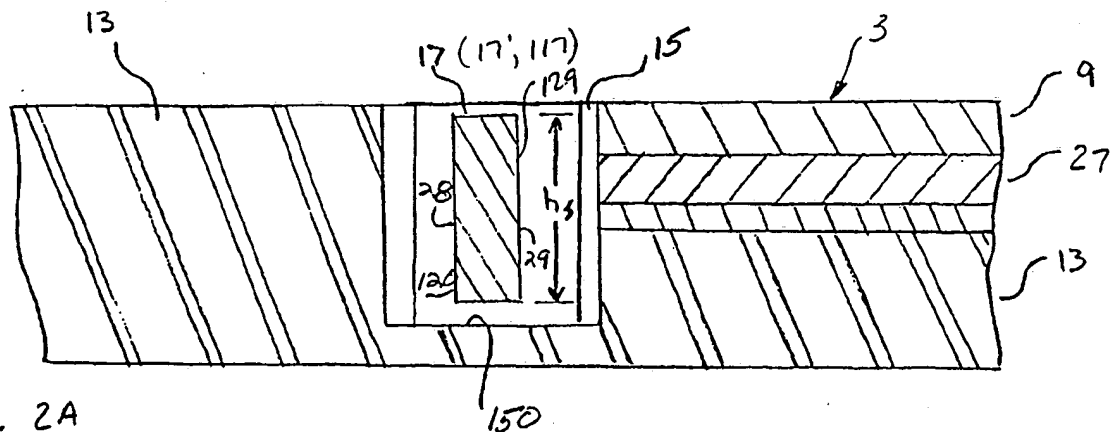


FIG. 2A

FIG 2B

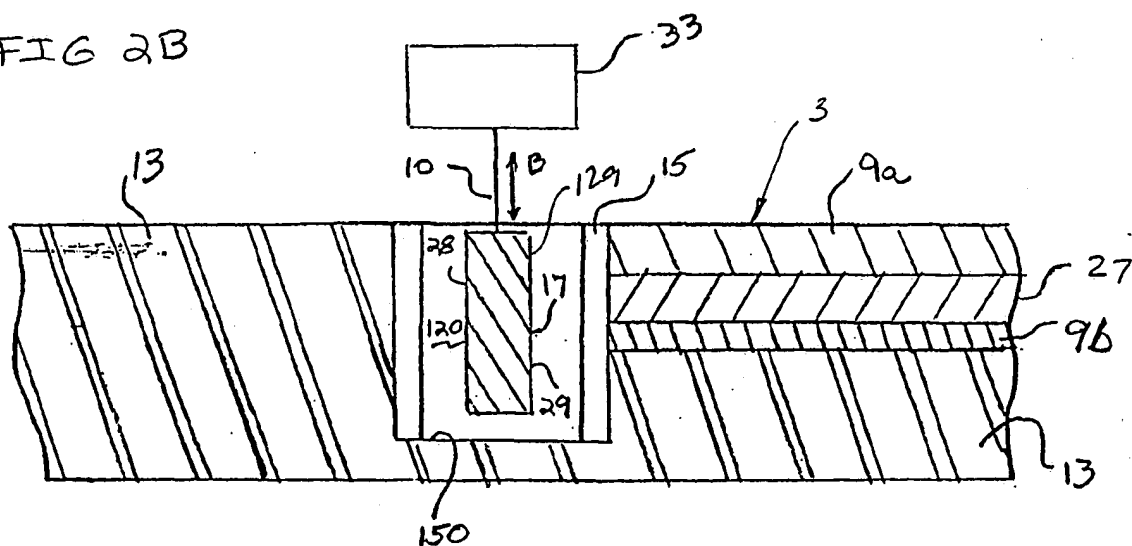


FIG. 3

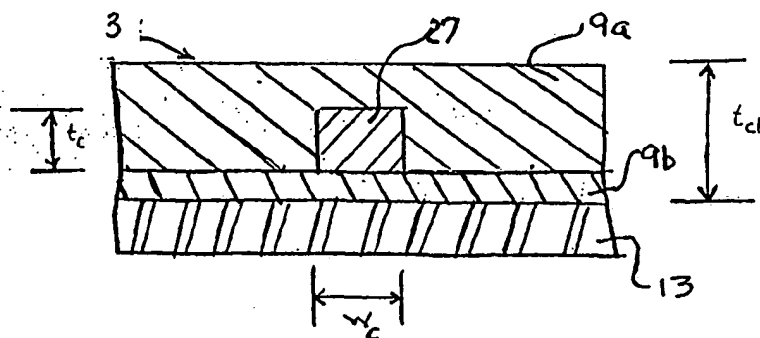


FIG. 4

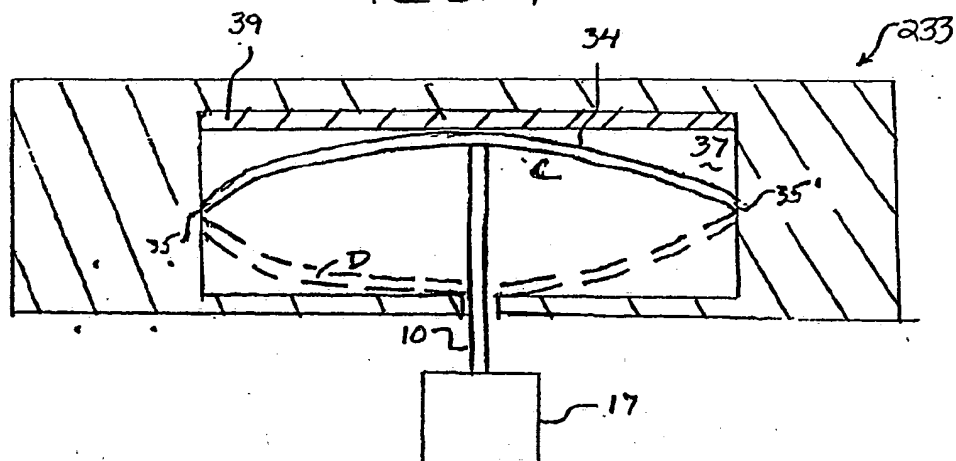
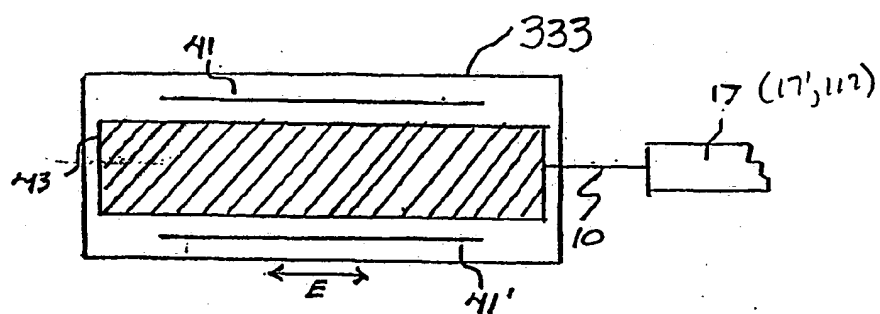
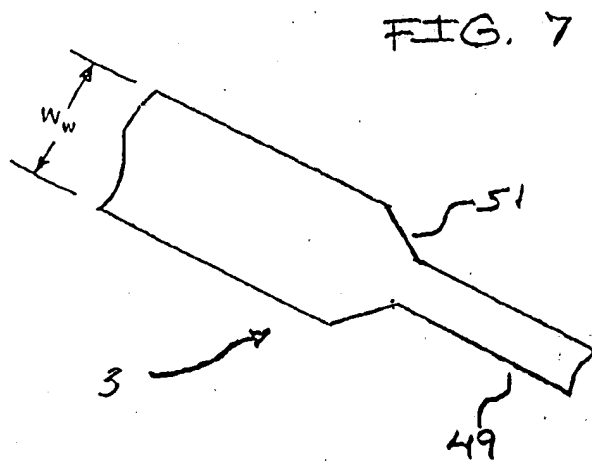
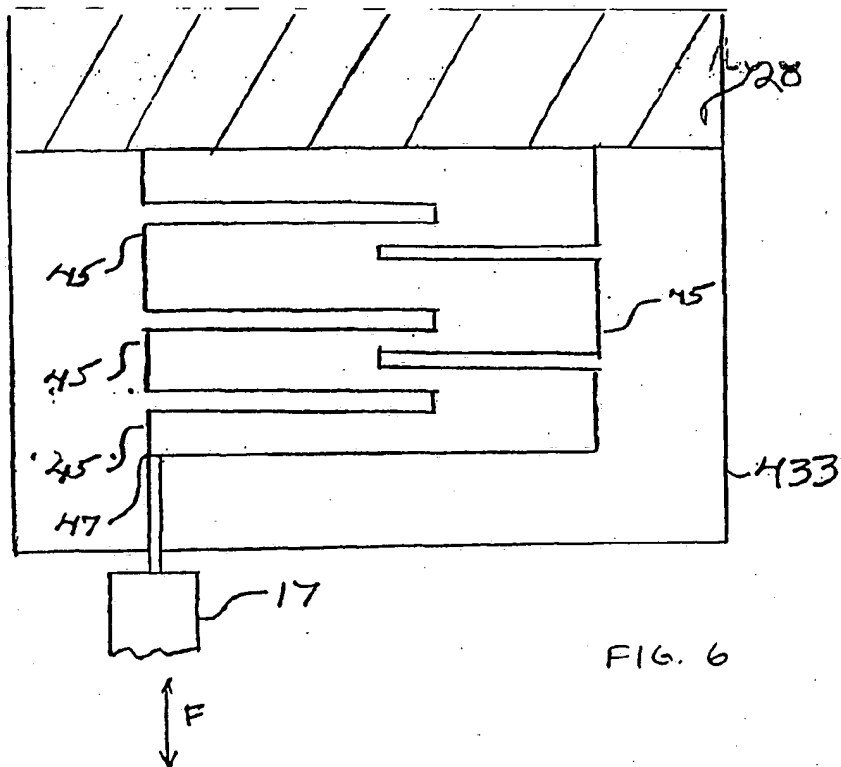


FIG. 5







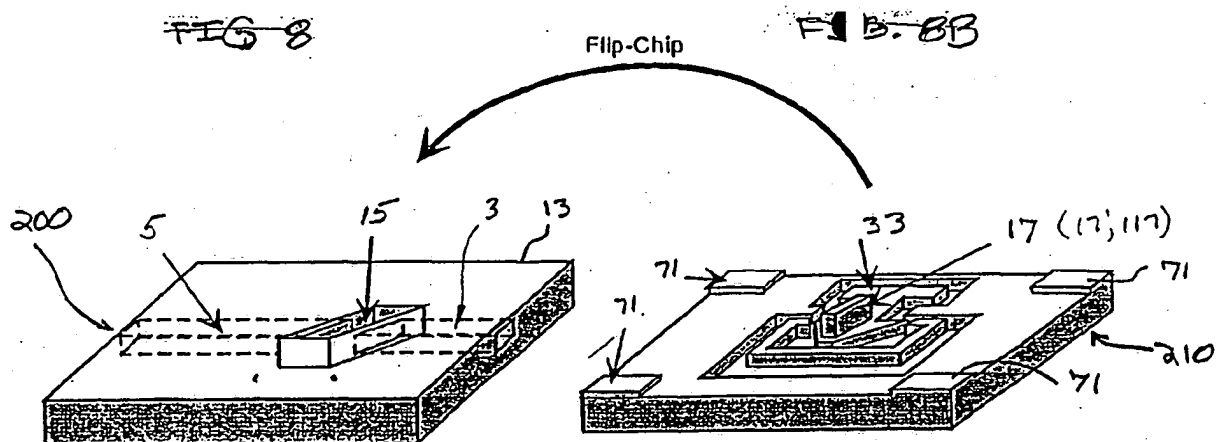


FIG. 8

FIG. 9A

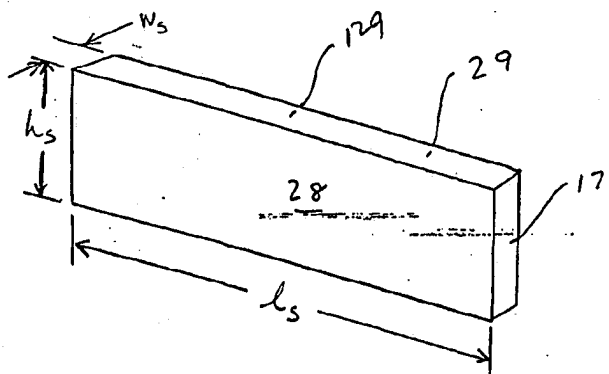


FIG. 9B

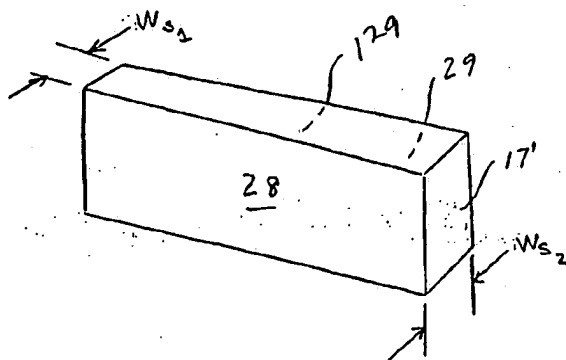


FIG. 10

